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SLR2000: EYESAFE AND AUTONOMOUS SINGLE PHOTOELECTRON SATELLITE LASER RANGING AT KILOHERTZ RATES

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ABSTRACT

SLR2000 is an autonomous and eyesafesatellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage. Replication costs are expected to be roughly an order of magnitude less than current operational systems, and the system will be about 75% less expensive to operate and maintain relative to the manned systems. Computer simulations have predicted a daylight tracking capability to GPS and lower satellites with telescope apertures of 40 cm and have demonstrated the ability of our current autotracking algorithm to extract mean signal strengths as small as 0.0001 photoelectrons per pulse from background noise.

The dominant cost driver in present SLR systems is the onsite and central infrastructure manpower required to operate the system, to service and maintain the complex subsystems (most notably the laser and high precision timing electronics), and to ensure that the transmitted laser beam is not a hazard to onsite personnel or to overflying aircraft. In designing the SLR2000 system, preference was given to simple hardware over complex, to commercially available hardware over custom, and to passive techniques over active resulting in the prototype design described here. This general approach should allow long intervals between maintenance visits and the “outsourcing” of key central engineering functions on an “as needed” basis. As a result, many of the signal extraction techniques and engineering designs employed here may have application in remotely operated or even spaceborne lidar applications.

SLR2000 consists of seven major subsystems: (1) Time and Frequency Reference Unit; (2) Optical Subsystem; (3) Tracking Mount; (4) Correlation Range Receiver; (5) Meteorological Station; (6) Environmental Shelter with Azimuth Tracking Dome; and (7) System Controller. The Optical Subsystem in turn consists of a 40 cm aperture telescope and associated transmit/receive optics, a passively Q-switched microlaser operating at 2 KHz with a transmitted single pulse energy of 135 μJ, a start detector, a quadrant stop detector for simultaneous ranging and subarcsecond angle tracking, a CCD camera for automated star calibrations, and spectral and spatial filters to reduce the daylight background noise. The meteorological station includes sensors for surface pressure, temperature, relative humidity, wind speed and direction, precipitation type and accumulation, visibility, and cloud cover. The system operator is replaced by a software package called the “pseudo-operator” which, using a variety of sensor inputs, makes all of the critical operational decisions formerly made by onsite personnel.

Keywords: laser ranging, microlasers, laser altimetry, lidar, single photon detection, meteorological instrumentation, satellites, autonomous instruments

1. INTRODUCTION

The feasibility of a fully autonomous, satellite laser ranging system operating at visible wavelengths with eyesafe energies (on the order of 100 μJ for a 30 to 40 cm telescope aperture) and high repetition rates (on the order of 2 KHz) was first postulated by Degnan[1], and some early concepts and analyses were described in 1994 at the Ninth International Workshop on Laser Ranging Instrumentation in Canberra [2,3]. At the Tenth Workshop in Shanghai China in November 1996, several papers were presented which gave a progress report on the engineering design of the overall SLR2000 system[4] and described in detail the microlaser transmitter concept and supporting analyses[5], the correlation range receiver algorithms and analysis [6], the results of system simulations[7], and even the feasibility of SLR2000 ranging over interplanetary distances to a compact asynchronous laser transponder incorporating many of the SLR2000 subsystems[8]. In the intervening ten month period, we have begun to receive significant funding for SLR2000 development which has already resulted in a further maturation and evolution in the SLR2000 system design. The present paper provides an updated account of the overall system design and its expected performance.

When designing an autonomous and inexpensive system such as SLR2000, it is necessary to make certain assumptions regarding the environment into which it will be placed since specifying an environment which is unrealistically isolated and forbidding will only drive up the fabrication and operational costs. Thus, the typical SLR2000 site is anticipated to have: (1) generally good weather and visibility; (2) good site stability with access to bedrock; and (3) easy access to basic services such as stable commercial power, communications (telephone, Internet), transportation (airports), "industrial level" security (i.e. limited personnel access), and janitorial/custodial services.

To keep construction and maintenance costs at a minimum, we have also adopted the following design philosophies:

(1) Use off the shelf commercial components wherever possible; this allows rapid component replacement and "outsourcing" of engineering support;

(2) Use smaller telescopes (i.e. diameter <50 cm) since this constrains the cost, size, and weight of the telescope which in turn drives the cost, size, and weight of the optical tracking mount;

(3) For low maintenance and failsafe reliability, choose simple versus complex technical approaches and, where possible, use passive techniques and components rather than active ones (e.g. eyesafe beams vs active radars, passive T/R switches, passively Q-switched lasers and, if necessary, passive multipass laser amplifiers).

Adherence to these fundamental assumptions and design philosophies has led to the SLR2000 design described here.

2. MAJOR SUBSYSTEMS

A block diagram of the SLR2000 system is shown in Figure 1. It consists of several major subsystems which are discussed in more detail in subsequent subsections.

2.1 TIME AND FREQUENCY REFERENCE UNIT

The purpose of this subsystem is twofold: (1) to provide accurate on station epoch timing to simplify and accelerate the acquisition and tracking of the satellite targets; and (2) to provide an accurate frequency source for the pulse time-of-flight measurements. The Hewlett Packard Model HP58503A GPS Time and Frequency Reference Receiver has been selected to serve as the baseline station clock and frequency reference for SLR2000. The unit uses timing information from the Global Positioning System (GPS) constellation of satellites to automatically constrain the long term frequency drift in a crystal oscillator, which has excellent short term stability, and provides clock outputs at both 1 Hz and 10 MHz.

The one pps output has a pulse-to-pulse jitter of less than 750 psec with only one GPS satellite in view. Its time accuracy, when locked to GPS, is specified at less than 110 nsec with respect to UTC (i.e. the master clock at the US Naval Observatory in Washington, DC). In the prolonged absence of a GPS signal (unlocked), the accumulated time error is less than 8.6 μsec in 24 hours. The 10 MHz output has a Root Allen Variance, when locked to GPS, of 1.5×10^{-11} for a 100 msec sample time typical of artificial satellite laser ranging and better than several parts in 10^{11} over time intervals from several minutes to an hour, corresponding to the duration of a typical satellite pass . Thus, systematic and random ranging errors introduced by variations in the clock frequency should be submillimeter for all satellites up to and including the highest satellites (GPS, GLONASS, and ETALON) at maximum slant ranges of 22,000 Km. We are also investigating a possible enhancement, i.e. a GPS-steered rubidium. The rubidium clock would bridge the temporal gap between the excellent short term (<1 sec) stability of the crystal oscillator and the good long term (> 1 hour) stability provided by GPS updates. The enhanced rubidium device is slightly more expensive (<$10K) but would provide significantly improved epoch timing (<30 nsec) and an order of magnitude better frequency stability over intermediate time scales on the order of several minutes to an hour.

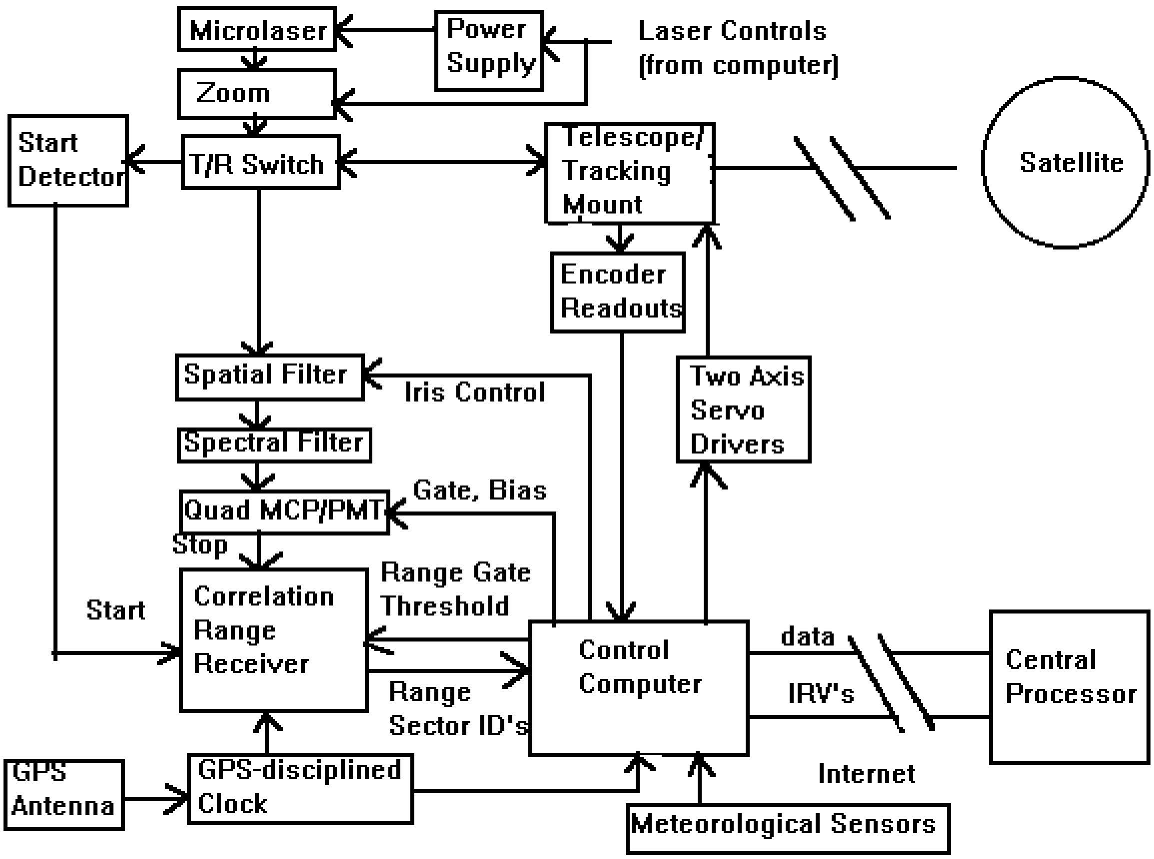

Figure 1: Simplified block diagram of the SLR2000 system.

2.2 OPTICAL SUBSYSTEM

The optical subsystem consists of the telescope, a passive transmit/receive (T/R) switch , a Q-switched microlaser operating at 2KHz, a start diode, a quadrant stop detector with bias supply and gating circuit, a CCD camera for automated star calibrations, and spectral and spatial filters. The outgoing single pulse energy is maximized, within eye hazard constraints, by filling the available telescope aperture with the transmit beam and by using a passive transmit/receive (T/R) switch to separate the transmitted and received beams.

We have recently selected a 40 cm off-axis parabolic reflector telescope for the prototype. This choice bypasses the pesky secondary mirror central obscuration associated with more common Cassegrain systems thereby eliminating the associated laser transmitter and receiver losses as well as the effects of the secondary "shadow" on the transmitter far field pattern. The use of Super-invar rod spacers, Zerodur mirror blanks, and reentrant fabrication techniques helps to passively maintain system focus over a very wide temperature range when the dome is open for operations. At a desired beam divergence of roughly 8 to 10 arcseconds, the laser must operate far from the diffraction limit of a 40 cm aperture, and therefore the laser transmit beam is slightly defocused.

A block diagram of the preliminary transceiver design, based on passive wavelength separation of the transmit and receive beams, is shown in Figure 2. We are also considering a simpler and more conventional polarization-based T/R switch option, and a final decision will be made pending field investigations into the effects of the uncoated TIR prisms on the LAGEOS and LAGEOS 2 satellites on the polarization of the reflected laser beam. Other passive T/R approaches, such as bistatic systems or aperture sharing of a monostatic system, were rejected since they introduced a minimum factor of 4 loss in signal return rate under the combined constraints of eyesafety and telescope aperture. The more conventional mechanical T/R approaches (such as rotating mirrors, wheels, or slits) were avoided because they offered no additional advantages, were ill-suited to Kilohertz repetition rates, and tend to lose phase lock over time due to mechanical wear.

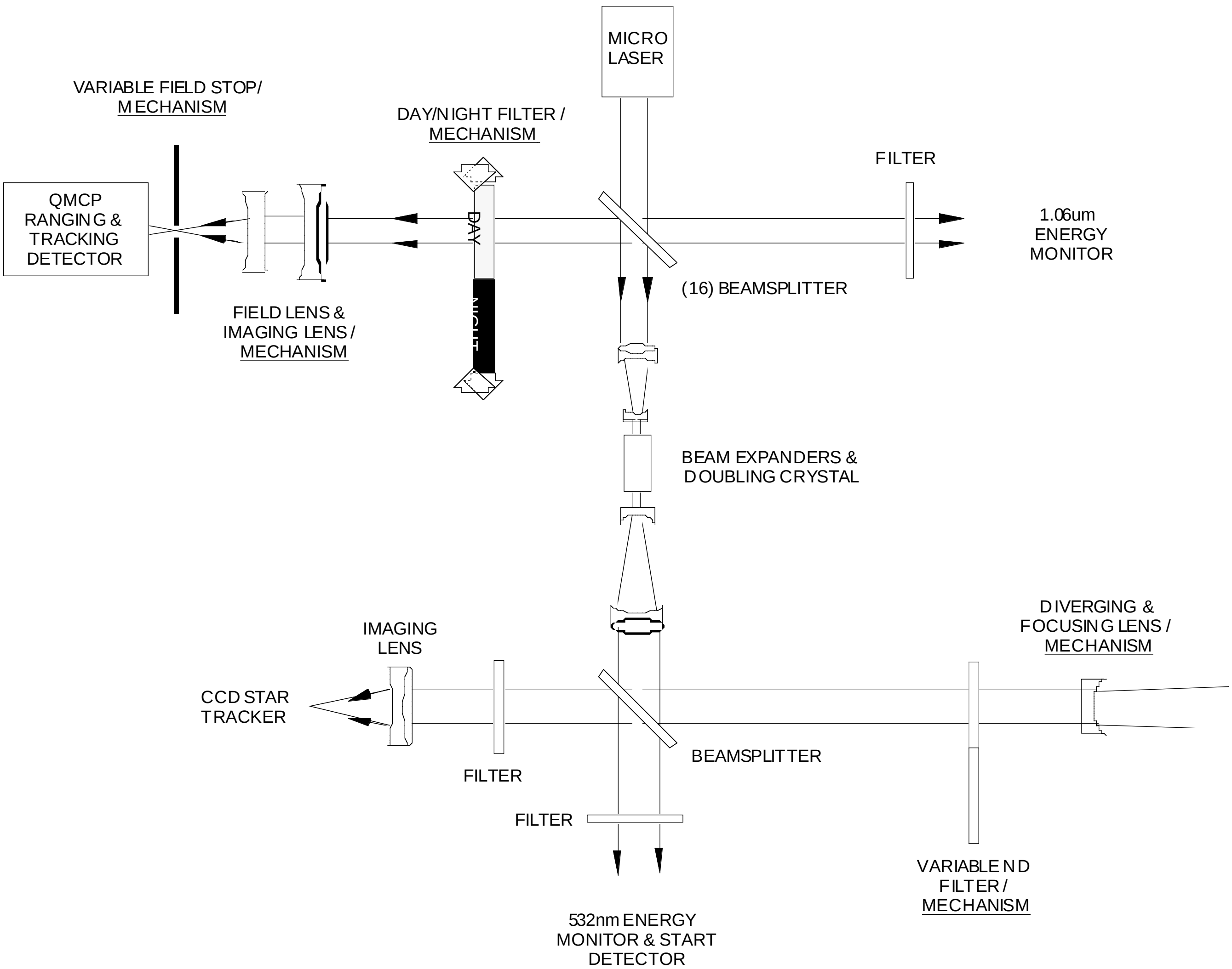

Figure 2: Optical block diagram of the SLR2000 transceiver using a passive wavelength T/R switch.

In the wavelength T/R scheme, a 2 KHz pulse train from the Nd:YAG microlaser transmitter is transmitted through a dichroic mirror which passes infrared radiation at 1064 nm and reflects the frequency doubled green radiation at 532 nm. In order to achieve the necessary doubling efficiency, the low energy pulse train is demagnified by a reversed telescope into a doubling crystal and the resulting green radiation at 532 nm is magnified and recollimated by a second telescope. After reflection from a second dichroic beamsplitter, which is coated to reflect the majority of the 532 nm radiation, a final diverging lens matches the outgoing transmitter beam to the focal length of the telescope primary for further magnification and collimation. The position of the diverging lens is adjustable under computer control and can be used to correct for any residual thermally induced focus variations in the telescope not taken out by the passive measures. The “leakage” of the transmit beam off the two beamsplitters is used to monitor the infrared and green energies from the laser and doubling crystal respectively. A bandpass filter blocks 1064 nm light from entering the green detector. The green radiation reflected from the satellite retraces the same optical path until it is reflected by the dichroic beamsplitter into the quadrant ranging and tracking detector after first passing through a narrowband spectral filter, an imaging lens, and a variable spatial filter. Thus, the combination of dichroic mirror and doubling crystal provides a passive, wavelength-dependent transmit/receive switch[9] which is independent of polarization and allows the entire telescope primary to be used simultaneously by both the transmitter and receiver.

Use of the alternative polarization T/R switch mentioned previously would introduce only minor modifications by (1) relocating the doubling crystal at the microlaser where the beam is already small and peak powers are high thereby eliminating the need for the two telescopes surrounding the doubling crystal; (2) replacing the dichroic beamsplitter with a polarizer; and (3) installing a quarter-wave plate to convert the outgoing tranmitter beam to circularly polarized light and the incoming received light to the orthogonal polarization.

During star calibrations, collimated starlight reflects off the dichroic beamsplitter , passes through a broadband filter centered on the 532 nm laser wavelength, and is focused by a lens onto a 324 x 242 pixel Electrim Model EDC-1000M CCD array which in turn measures the position of the star and provides pointing error information to the system computer for periodic mount modelling and pointing verification. The array is also used to periodically check and verify accurate system focus by minimizing the star spot diameter. The star calibration optical train provides a field of view of approximately two arcminutes.

The quadrant stop detector lies behind the focal plane so that the incoming reflected laser energy and background noise is spread over the four quadrants, allowing estimation of the position of the satellite in the receiver field of view by the correlation range receiver as described in Subsection 2.4.3. The detector is a fairly modest modification of a conventional microchannel plate photomultiplier in which the usual single element anode is replaced by a quadrant anode, each outputting to its own SMA connector.

To achieve eyesafety, the single pulse energy is reduced by almost three orders of magnitude relative to current systems (from 100 mJ to 133 μJ) and the transmit beam is magnified to fill the available telescope aperture (40 cm). To compensate for this factor of a 1000 loss in signal strength, the repetition rate is increased from a nominal 5 Hz to 2 KHz (x 400) and the transmitter beam divergence is reduced from a nominal 25 arcseconds to about 8 arcseconds (x 9). To attain the same ranging accuracy, we wish to retain pulsewidths comparable to modelocked lasers, i.e. on the order of 100 picoseconds or less. All of these specifications fit comfortably within the domain of the passively Q-switched microlaser[10].

Compared to the large and highly complex modelocked Nd:YAG laser oscillator/amplifier systems currently used in SLR field systems, the microlaser is an exceedingly simple, highly reliable, and extremely small device (on the order of a few mm in length). It is end-pumped by a fiberoptic bundle carrying a few watts of CW optical power from a diode laser array operating in the Nd:YAG pump band at 808 nm. It is passively Q-switched by a thin (≅ 1 mm) Cr^{4+}:YAG crystal. The ultrashort resonator length combined with typical laser metastable state lifetimes results in the generation of a continuous train of short optical pulses, on the order of 100 picoseconds in width, with repetition rates in the kilohertz regime[10]. Furthermore, the microlaser's TEM_{00} output simplifies the achievement of narrow beam divergences. At NASA/GSFC, we are attempting to optimize the performance of these lasers for the SLR2000 application using recently developed models[5,11].

2.3 TRACKING MOUNT

The telescope will be mounted in one of the Aerotech Model AOM360-D series of tracking mounts, to be selected upon completion of the optical head preliminary design. The latter mounts can accommodate telescopes up to 50 cm in diameter and are driven by direct-drive DC torque motors. The absence of gear trains and other drive mechanisms eliminates position error contributions due to mechanical hysteresis and backlash. The mount has a high axis positioning accuracy of one arcsecond, a bidirectional repeatability to one arcsecond, and a low axis wobble, also at the few arcsecond level. Orthogonality of the axes is good to 3 arcseconds, but this error can be taken out with star calibrations and mount modelling software. Thermal stability is 0.4 arseconds/^{o}C. The use of Inductosyns, rather than optical encoders, for angle sensing allows optical beams and/or electrical cables to be passed from the telescope to the transceiver through the center of the azimuth and elevation drive bases. The mount will be equipped with military style electrical connectors and bearing seals to provide additional environmental protection over and above that provided by the observatory dome.

2.4 CORRELATION RANGE RECEIVER (CRR)

The correlation range receiver, in conjunction with the autotracking software, performs several critical functions which include: (1) precise time of flight (TOF) measurements; (2) the discrimination of signal from noise; and (3) the generation of subarcsecond pointing corrections. The power of the CRR is that it carries out these functions simultaneously using all of the ranging signal available to it. Like the microlaser transmitter, the CRR must operate at KHz rates. To fully understand the design and operation of the CRR, one must first describe the manner in which the TOF measurement is made under these high repetition rate conditions.

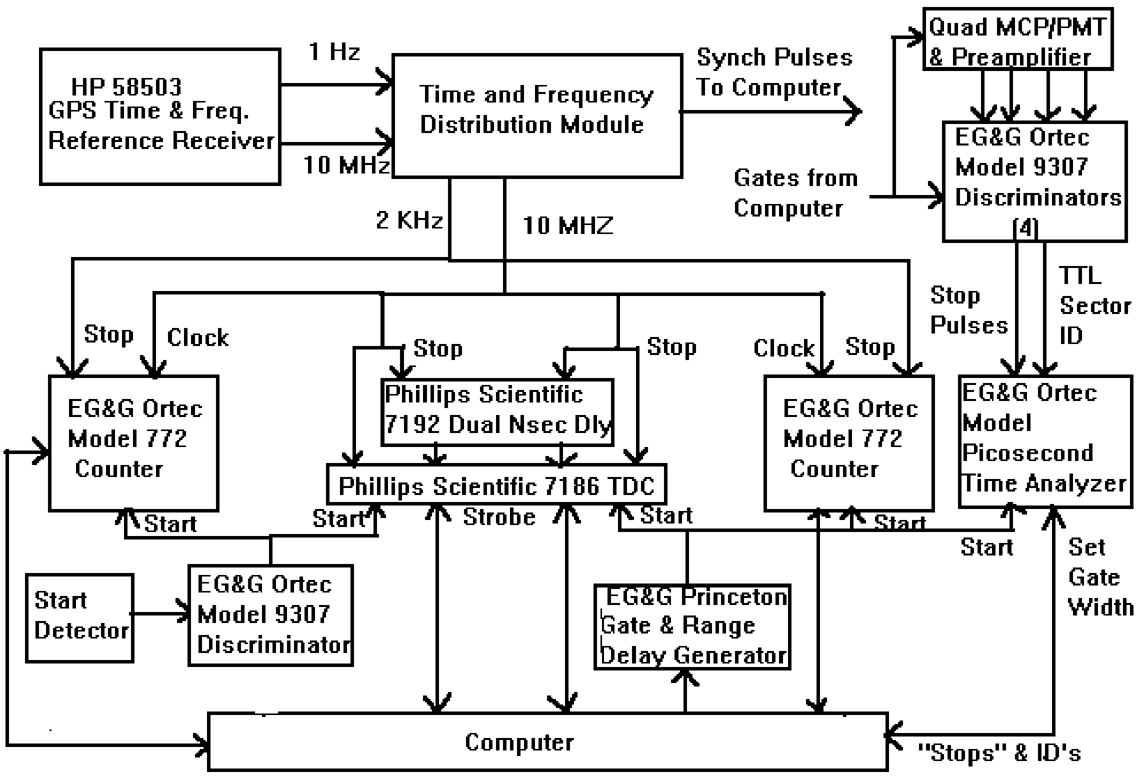

Figure 3: A correlation range receiver configured from commercially available nuclear timing instrumentation.

2.4.1 CRR TIME-OF-FLIGHT MEASUREMENT

Figure 3 shows a sample CRR configuration which is built up entirely from NIM/CAMAC nuclear timing instrumentation commercially available from three companies: EG&G Ortec, EG&G Princeton and Phillips Scientific. In this particular embodiment of the CRR, the timing is centered around the nominal 2 KHz fire rate of the microlaser transmitter as illustrated by the timing diagram in Figure 4. The 10 MHz output of the HP Time and Frequency Reference Receiver is used to generate a 2 KHz train of synchronized clock pulses. Within each 500 µsec fire interval, there will be one "start" pulse and potentially one "stop" pulse plus noise counts. Since each fire interval corresponds to a one-way distance interval of only 75 Km, there are many pulses in flight at any given time and therefore the stop pulse occurring during satellite ranging in the (n+m)th interval originates from the "start" pulse occurring in some earlier (nth) interval. The (n+m)th start pulse starts the "start" counter for that interval and starts a time to digital converter (TDC) which is then stopped by the next 10 MHz clock pulse. The arrival of the (n+m)th clock pulse stops the "start" counter. Thus, the temporal position of the "start" laser pulse within the fire interval is determined by adding the "start" counter and "start" TDC vernier outputs. Similarly, the range gate from the EG&G Princeton Research Gate and Time Delay Generator starts a second "stop" counter, a second "stop" TDC, and an EG&G Model 9308 Picosecond Time Analyzer (PTA). The "stop" TDC is stopped by the next 10 MHz clock pulse and the "stop" counter is stopped by the next 2 KHz clock pulse. Adding the outputs of the second TDC vernier and the "stop" counter gives the time interval between the range gate and the (n+m+1)th 2 KHz clock pulse. The PTA is capable of recording multiple events separated by at least 50 nsec and gives the temporal positions of any signal or noise counts occurring within the range window relative to the range gate. The width of the PTA range window is programmable down to a minimum of 80 nsec, and the time resolution of the PTA is the range window divided by 64,000 (or about 1.2 psec for its narrowest 80 nsec setting). Thus, all "events" occurring within each 500 µsec fire interval are well-positioned with respect to the 2 KHz clock pulses which bound that interval.

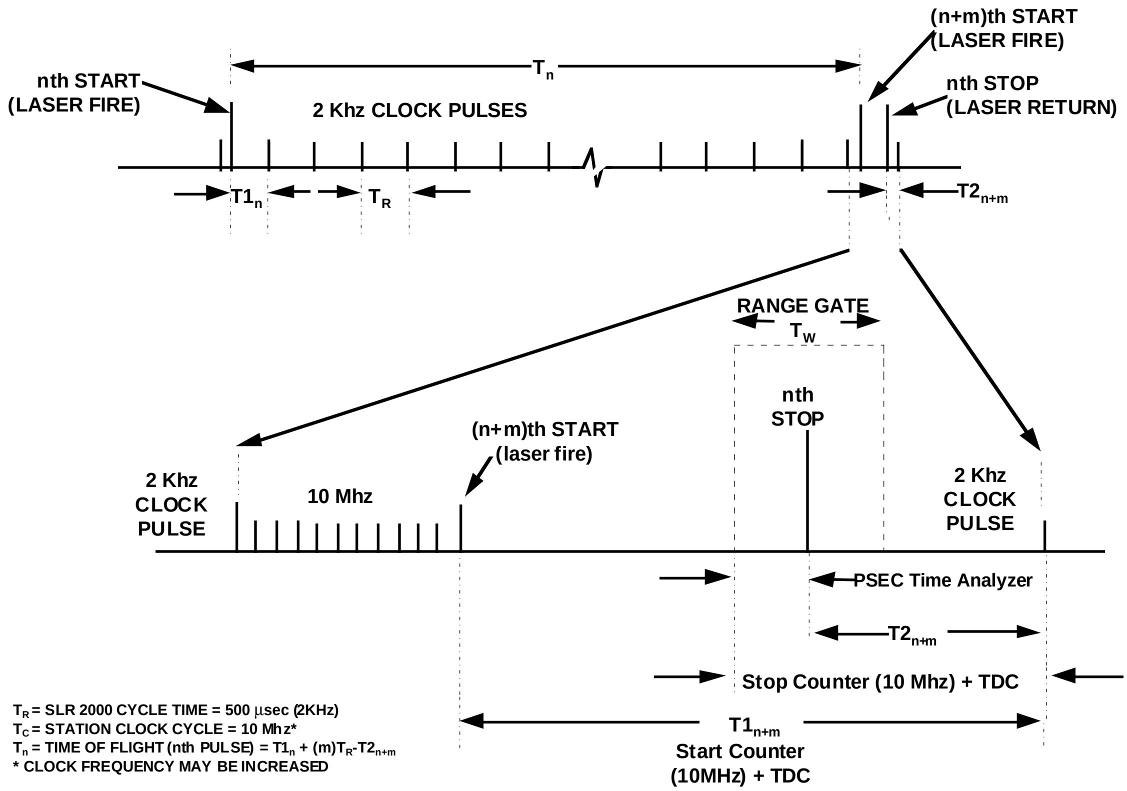

Figure 4: SLR2000 Timing Diagram

To compute the range to the satellite as measured by the nth start pulse, one must now use the following formula (see Figure 4)

$$T_n = T1_n + mT_R - T2_{n+m}$$

where $T1_n$ is the interval between the nth start pulse and the (n+1)st 2 KHz clock pulse as measured by the "start" counter and "start" TDC, T_R = 500 µsec is the fire interval between 2 KHz clock pulses, $T2_{n+m}$ is the interval between the (n+m)th signal arrival time and the (n+m+1)th clock pulse as measured by the "stop" counter, "stop" TDC, and PTA, and m is the number of intervening 2 KHz clock cycles between a "start" pulse and its corresponding "stop" pulse and can be computed a priori from our approximate knowledge of the station and satellite positions.

We are also investigating possible enhancements which would improve the timing precision of the baseline CRR, such as modifying the range gate generator and event timer developed by AlliedSignal Technical Services Corporation (ATSC) for the Matera Laser Ranging Observatory[12] (MLRO) to perform all of the CRR functions. The unmodified MLRO event timer has already demonstrated a single shot one sigma RMS of 5 mm in multiphotoelectron ranging to the LAGEOS satellite which is almost a factor of 2 better than is achieved with the Hewlett Packard HP5370B Time Interval Unit which is the current standard in NASA SLR systems.

2.4.2 POST-DETECTION POISSON FILTERING OF RANGE DATA BY THE CRR

All timing outputs from the CCR (starts, stops, and noise events) are transferred to the SLR2000 ranging computer which assigns them to "time bins" in accordance with satellite-dependent algorithms described in detail by Titterton and Sweeney[6] and simulated simulated by McGarry[7]. Signal counts from the satellite would be bunched in a narrow time interval whereas dark current or background noise counts would be spread over the full width of the range gate. Put simply, the ranging computer looks at the number of counts in each time bin to identify the probable presence of the signal, applies an iterative filter, computes an updated range and time bias, and gradually reduces the range gate width to decrease the number of noise counts in future frames.

Based on a knowledge of the noise Poisson statistics, the CRR Algorithm[3] produces a histogram which is used to distinguish signal from noise. While the noise rates can be very high ($\geq$50,000 counts per second), the temporal duration of the range window limits the actual noise counts received. With a sufficiently small window (<10 μsec), the distribution of the noise becomes fairly uniform, and will produce, on average, uniform counts across all bins of a histogram formed in this range window space. When the bin size is correctly chosen, the signal returns will all fall within a single histogram bin, resulting in a count that is significantly larger than the other bins. Choosing the length of time to collect histogram data (called a frame) before analysis is also important for this algorithm. With a longer frame time, more noise collects in the bins, and the signal itself may eventually spill into an adjacent bin due to imperfect orbit predictions or onsite time bias. If the frame time is too short, there may be not enough signal returns to adequately discriminate against the noise background.

Our goal in the development of the CRR was to achieve at least a 90% Probability of Satellite Detection (Acquisition), with less than 1% Probability of False Acquisition for low and medium altitude satellites (up to LAGEOS altitudes of 6000 Km) and less than 10% False Acquisition Probability for the higher satellites such as ETALON and GPS at 20,000 Km. Analysis[13] has shown that the histogram technique described above (called the "Single Frame Algorithm") will produce the desired results for most of the satellites that are currently tracked by lasers. The algorithm sets up the frame time to achieve an expected number of 10 signal returns, and then picks as signal any bin with 6 or more counts. Three representative satellites with corresponding algorithm parameters are given in Table 1 for daylight pass acquisition using a system with a 40 centimeter telescope, $\pm$25 microradian receiver field of view, 133 microjoule transmit energy, $\pm$20 microradian laser divergence, and a 0.5 microsecond range window. The total atmospheric transmission was assumed to be 0.1 at 20 degrees elevation and 0.3 at 30 degrees.

Satellite	Altitude (Km)	Acq. Elevation (deg)	Expected Signal (pe/pulse)	Frame Length (sec)	Noise Cts/Frame
STARLETTE	**800**	**20**	**0.0090**	**0.6**	**30**
LAGEOS	**5900**	**20**	**0.0004**	**12.5**	**625**
ETALON	**19000**	**30**	**0.0004**	**12.5**	**625**

Table 1: SLR2000 daylight satellite acquisition

For all satellites that are regularly tracked, orbit predictions are good and a histogram bin size of about 0.5 nanosecond represents the optimum choice since it can accomodate both the single shot range noise as well as nominal time biases at the station. Thus, in a 0.5 microsecond range window, there will be 1000 histogram bins. Spreading 625 noise counts over the 1000 histogram bins results in an expected noise count per bin per frame of 0.625, making 6 or more noise counts in a single bin a very low probability event.

Another technique which has promise for satellites whose predictions are not as well known is to look at multiple frames instead of single frames. In this technique, N frames of M must all have a histogram bin with 6 or more counts to achieve acquisition. Preliminary results for the 2 out of 3 case demonstrate that this technique is better able to handle high noise counts than the single frame technique, and it is possible to reduce the single frame probability of acquisition to less than 90% and still be able to achieve an M frame probability of 90%. This permits a reduction in the single frame time and may permit acquisition of a signal that is walking through adjacent bins as a result of prediction errors.

2.4.3 DERIVATION OF SUBARCSECOND POINTING ERROR USING THE CRR

As mentioned in Section 2.2, the stop detector is placed behind the telescope focal plane so that the satellite image is enlarged and distributed over the four quadrants as in Figure 5. Following a photon event in one of the quadrants, the corresponding anode produces an electronic pulse which is input to one of four EG&G Ortec Model 9307 "Pico-timing Discriminators". The latter device produces both a fast ECL logic "stop" pulse, which is summed with the other three discriminator channels and input to the PTA timing circuitry, and a second TTL logic pulse, which is input to a second circuit in the PTA and identifies which of the four quadrants the timing signal came from. One would expect, on average, that noise counts would be equally distributed among the four quadrants whereas, if there were a small pointing error, signal counts would pile up preferentially in one or more quadrants. Following the filtering of noise counts based on time of arrival by the postdetection Poisson filter, a subarcsecond pointing angle correction can be computed by adding or subtracting the residual counts in each quadrant using the algorithms summarized in Figure 5.

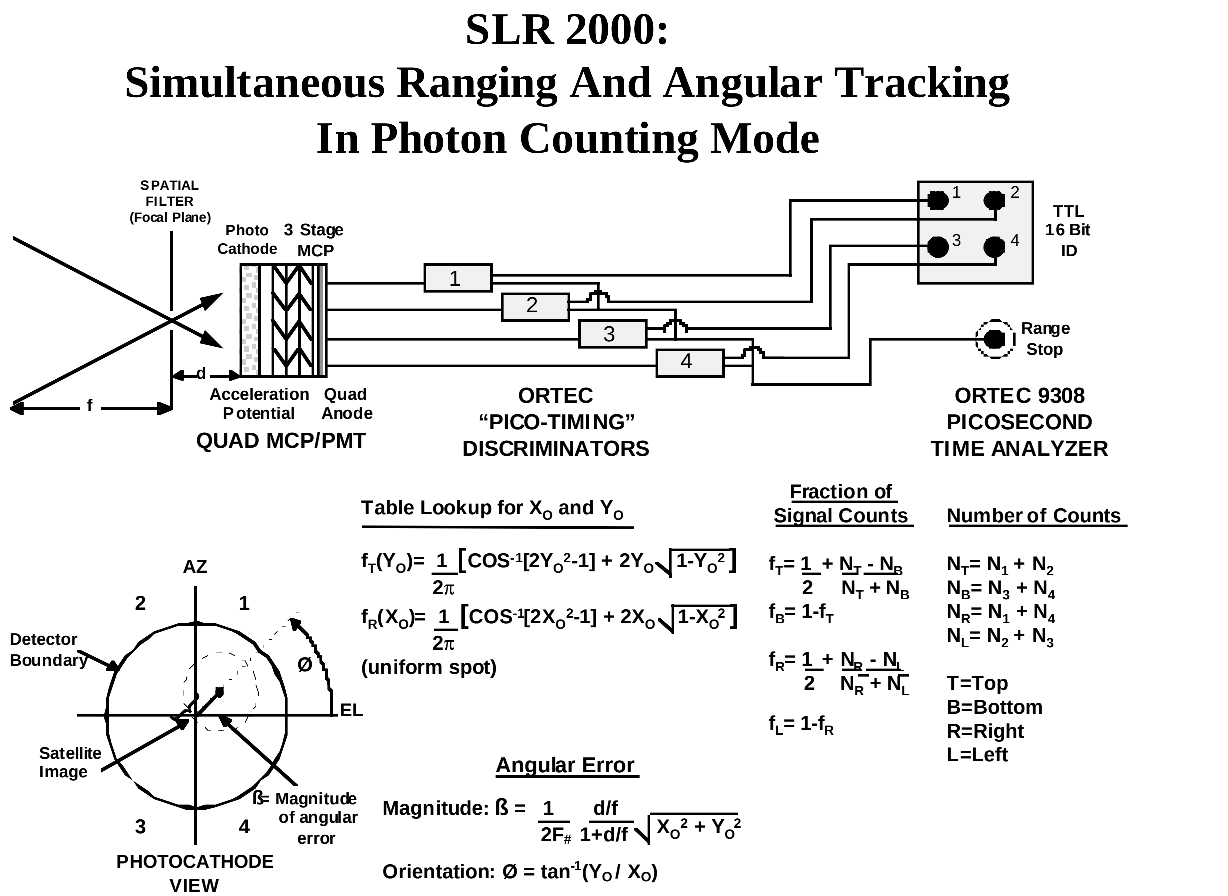

Figure 5: Correcting pointing error in the photon counting mode using the correlation range receiver.

2.4.4 SIMULATED PERFORMANCE OF THE CRR

The SLR2000 Simulator is a software package which permits testing of autotracking algorithms prior to hardware development. It currently runs on an HP735 and models the relevant errors in the timing, tracking, receiver, laser and environment[7]. The outer shell of the program keeps track of which returns are signal and which are noise and is therefore able to correctly assess the performance of the inner core of autotracking algorithms. Output is displayed in the form of an Observed minus Calculated (O-C) plot of the range data. Figure 6 shows the Correlation Range Receiver Single Frame Algorithm performance for a daylight pass of LAGEOS. Small dots indicate noise and darker squares are signal. Due to unmodellable errors in the mount pointing as well as small prediction errors, the autotracking algorithm must first search for the satellite by scanning angularly. This angular search for the satellite is reflected in the time period at the start of the pass where no signal is seen. It is important to note that during this period the algorithm does not mistake noise for signal. Once the algorithm finds satellite returns, it calculates the required biases to both center the range returns in the window and center the laser beam on the satellite. In the plot, the centering of the signal in the range window implies the algorithm is correctly tracking the satellite.

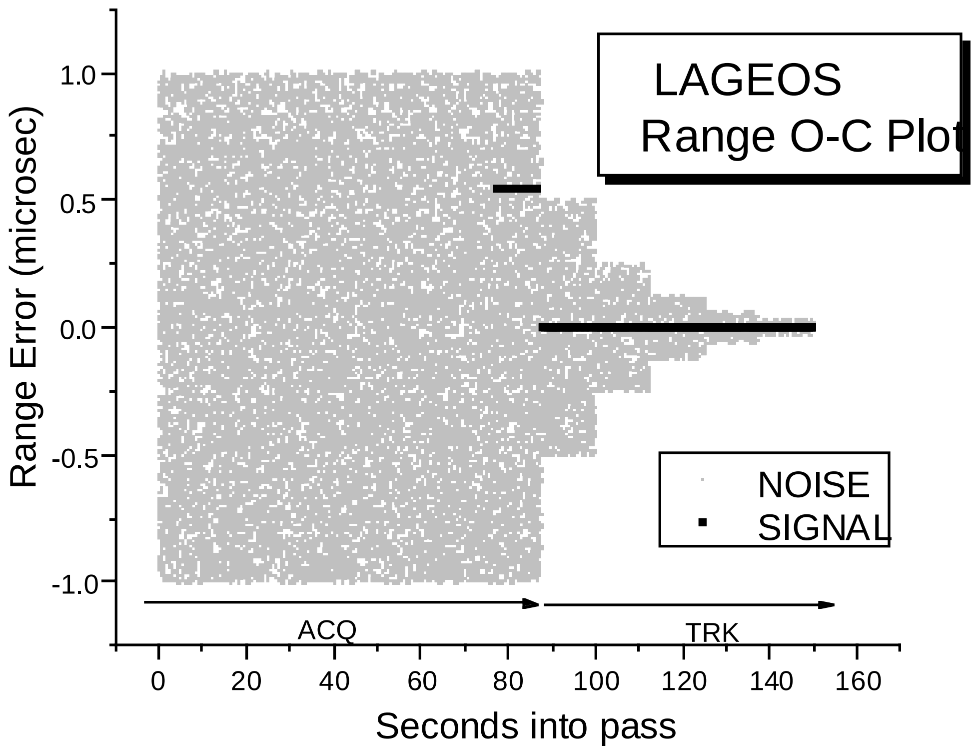

Figure 6: Simulated performance of SLR2000 acquiring the LAGEOS satellite in full daylight at an elevation angle of 20 degrees. During the first 70 seconds, the system conducts a spiral scan searching outward from the satellite's predicted position which the simulator purposely caused to be in error by about a beamwidth. The CRR acquires the signal quickly following initial ilumination of the target about 75 seconds into the pass, recognizes and corrects for a range bias of 0.5 μsec to center the signal in the gate, and continually narrows the width of the range gate from an initial value of $\pm$ 1 μsec until the background noise is nearly eliminated 140 seconds into the pass.

Backscattered radiation adds a range-dependent noise rate on top of a constant background and detector dark count noise rate and can be substantial for some interval of time following the laser fire. Light scattered from optical surfaces traversed by the transmitted pulse as it exits the system or from clouds at altitude is of relatively short duration compared to the 500 μsec time interval between the nominal Q-switched laser pulses and therefore of little consequence. Furthermore, gating of the acceleration grid in the microchannel plate photomultiplier prevents secondary electron generation in the microchannels and tube saturation except for a narrow time interval when the pulse is expected to arrive.On the other hand, molecular and aerosol back scattering in the atmosphere lasts significantly longer. If the nominal height of the atmosphere is 20 Km and the 500 μsec fire interval corresponds to a 75 Km range, then potentially 25% to 75% of the fire interval is subject to this additional noise at elevation angles between 90 and 20 degrees respectively. Loss of this large a fraction of the fire interval to backscatter noise would be unacceptable, and therefore provisions are being made to adjust the laser repetition rate over a narrow range to prevent the "stop" pulse from arriving during whatever "receiver blanking period" is necessary. We are presently incorporating the backscatter effect into our system analyses and simulations.

2.5 METEOROLOGICAL STATION

The meteorological subsystem measures pressure, temperature, and relative humidity with the requisite accuracy for supporting atmospheric models used in applying the atmospheric correction in subcentimeter laser ranging[14]. In order to protect the system from the external environment and extend component lifetimes, the meteorological subsystem also monitors: (1) wind speed and direction ; (2) the presence, type, and accumulation of various forms of precipitation (rain, snow, etc.); (3) local visibility out to 50Km; and (4) cloud cover.

The meteorological station consists of four major components:

(1) Paroscientific MET3-1477-001 Pressure, Temperature, and Relative Humidity Monitor

Pressure: Range 800 to 1100 mbar; Accuracy ~0.1 mbar; Stability < 0.1 mbar/year
Temperature: Range -40 to 70°C; Accuracy < 0.5°C; Stability < 0.1°C/year
Relative Humidity: Range 0 to 100%; Accuracy ±2%, Stability<1%/year

(2) Vaisala FD12P Precipitation and Visibility Sensor

The FDP12 consists of an optical transmitter, receiver, controller, and a capacitive rain sensor. It utilizes an optical forward-scatter sensor that not only sees fog but also distinguishes between precipitation particles. An ambient temperature sensor is included to increase the reliability of precipitation type assessment. The unit measures visibility optically from 10 m to 50 Km and the type, intensity, and accumulation of precipitation.

(3) Belfort 200 Wind Monitor

Wind speed is sensed by an 18 cm diameter helicoid propellor. A six pole permanent magnet attached to the shaft induces a sinusoidal AC signal in a stationary coil with a frequency proportional to the wind speed. Wind direction is sensed by rotation of the sensor on its vertical shaft Vane position is transmitted by a 10K ohm conductive potentiometer. With a reference voltage applied to the potentiometer, an analog voltage proportional to azimuth angle is produced as output.

Wind Speed: Range 0 to 135 mph; ±0.6 mph
Wind Direction: Range 0 to 360°; Accuracy ±3°

(4) Cloud Sensor

After considering several options for detecting clouds, which included visible sensors and a separate lidar channel, we have chosen a thermal infrared "all-sky" digital camera which operates in the wavelength regime between 8 and 12 microns. In preliminary tests, an Inframetrics Thermasnap™ camera, containing an uncooled 120 x 120 pixel silicon thermoelectric IR detector array, was placed above a conventional convex security mirror overcoated with gold in order to photograph the cloud cover down to 30 degrees elevation in a single frame. Each pixel senses the temperature of the sky within its field of view. The camera has a temperature measurement range from -20 °C to 350°C, a digitizing resolution of 16 bits, and can be operated under computer control. Low lying cumulus cloud temperatures tend to follow the lapse rate with altitude and hence are at significantly higher temperatures (10-20°C) than the higher cirrus or clear sky backgrounds. The instrument appears to work equally well under daylight or night conditions. The resulting "cloud mask" , combined with the wind, visibility, and precipitation sensors, assists the software "pseudo-operator" in deciding whether or not to open the observatory dome and begin laser operations. Based on cloud distribution, the "pseudo-operator" can also decide which satellites to track and over what portions of the orbit.

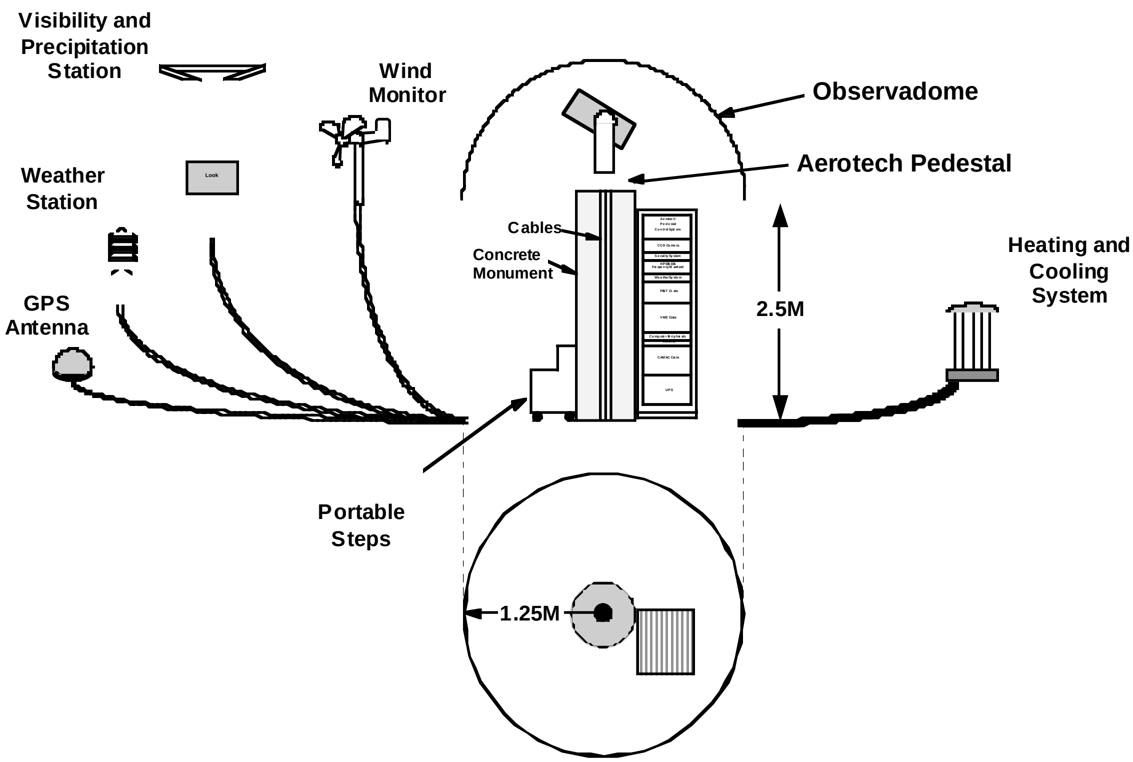

Figure 7: SLR2000 field installation concept.

2.6 ENVIRONMENTAL SHELTER AND AZIMUTH TRACKING DOME

The Aerotech tracking mount will be positioned (three-points of contact) and leveled, using two attached differential leveling bubbles, on a central concrete monument. A mount model, updated by frequent star calibrations, further defines and maintains the system orientation and alignment. The telescope and calibration targets will be more than 2 meters off the ground, making access by unauthorized personnel difficult.

The central monument sits inside an environmental shelter and a protective astronomical dome as in Figure 7. The interior of the environmental shelter is maintained at nominal room temperature (≅23^{o}C) by an external heat pump. This helps to stabilize the temperature of critical elements in the optical transceiver and the timing electronics and provides a comfortable workplace for visiting maintenance personnel. To allow the telescope and tracking mount to follow the external ambient temperature and thereby minimize thermal gradients in the telescope during system operation, the heated (or cooled) "electronics room" is thermally isolated from the dome area by a removable "ceiling". During maintenance, a technician can gain access to the telescope and tracking mount by removing the "ceiling" and using a set of portable steps permanently stored in the shelter. Diagnostic tests can be performed onsite by plugging a laptop computer into the central computer system. Internet and telephone communications are also provided in the shelter. A modem provides a backup means of communicating with the system when the Internet is inaccessible.

The 2.5 meter diameter dome will have a motorized open slit (shutter) and azimuth drive. Both are under computer control and the dome azimuth drive is slaved to the Aerotech tracking mount azimuth. After much technical debate, an open slit was chosen over a sealed dome due to concerns associated with our ability to preserve the narrow beam divergence and overall beam quality of the transmitter in the presence of a large (50 to 60 cm) transmitting optical window which (1) is expensive, (2) is subjected to a strong thermal gradient between the temperature controlled dome and the ambient atmosphere, (3) potentially creates strong thermally-driven air turbulence at the exit face which further disturbs beam quality, and (4) requires some form of condensation prevention/control. In order to maximize the alignment stability, the fixed optical transceiver, which resides in the temperature controlled area, will be rigidly mounted to the base of the azimuth drive and greatly simplifies system cabling. Optical beams can be passed between the telescope and transceiver through the center of the Aerotech azimuth stage Inductosyn via a Coude optical system extending through one arm of the mount yoke and then through the annular elevation Inductosyn. Sensitivity to small optical misalignments potentially introduced by the Coude optics and/or the mount axis bearings are greatly reduced by the high magnification of the optical telescope.

The shelter will also be equipped with additional inexpensive security devices for automatically detecting and reporting threats to system security, via Internet and/or recorded phone messages. These include motion and intrusion sensors and surveillance cameras for detecting and reporting unauthorized personnel in the vicinity, thermal sensors for detecting heat pump failure, power/voltage monitors, etc. Key security components, such as the computer and selected sensors, will be protected by UPS, and the safe default mode for key subsystems will be “Power Off” in the event of a power failure.

2.7 SYSTEM CONTROLLER

The SLR2000 computer consists of three Pentium-based processors, two in a VME backplane and the third in a PC/ISA crate. The VME bus was chosen for its higher bus speed (40MB/sec), while the ISA bus was needed to handle specialized interface cards for the camera, Picosecond Time Analyzer, and mount. The ISA computer functions simply as an Input/Output processor, passing data to and from the VME computers via shared memory. The VME processors perform all of the decision making, data analysis, and external communication. One of these processors, called the "Pseudo-Operator", performs the functions of a human operator, making decisions on whether the weather permits opening the dome and tracking, which satellite should be tracked, and whether the returns in the ranging window are signal or noise. The Pseudo-Operator also monitors the system temperatures and voltages, and acts to protect the system if it detects system health or safety problems. The second VME processor, called the Analysis CPU, computes the Normal Point data from the raw tracking/ranging data and sends this data out to a central archive. This processor also gets predictions for the system, and converts it to the appropriate format. Information is communicated between the two VME processors via file and memory sharing. Both processors will be using a UNIX operating system.

Human interaction with the SLR2000 system requires communicating with the Analysis CPU through the internet. A laptop PC running a special software package will allow personnel to monitor the operation of the system via graphical displays, get information from the system to analyze off-line, run diagnostic tests, and change system parameters.

3. SUMMARY

SLR2000 is an autonomous, eyesafe satellite laser ranging station with an expected single shot range precision of about one centimeter and a normal point precision better than 3 mm. The system will provide continuous 24 hour tracking coverage for all satellites up to and including GPS and will greatly reduce replication,, operating and maintenance costs. In designing the SLR2000 system, preference was given to simple hardware over complex, to commercially available hardware over custom, and to passive techniques over active resulting in the prototype design described here. It is hoped that this general approach will allow long intervals (months) between maintenance visits by technical personnel and the “outsourcing” of key central engineering functions on an “as needed” basis. In unassembled “kit” form, the per system hardware costs for SLR2000 are currently estimated to be about $320K. A fully assembled and tested field system, including shelter and monument, should be reproducible for about $550K per system in quantities of eight or more. This represents roughly an order of magnitude reduction in system replication costs relative to the current state-of-the-art. We are in the process of testing many of the subsystems now and hope to begin field tests of the SLR2000 prototype in late Spring, 1999.

We believe many of the subsystems being developed for SLR2000 may be of interest to other segments of the lidar community. Clearly, many of the subsystems and software packages being developed for SLR2000 are related to full system automation and have wide applicability to remotely operated or autonomous lidars. The use of high repetition rate microlasers and high sensitivity correlation receivers may find application in the next generation of spaceborne altimeters where there is a need for greater spatial resolution and improved power efficiency and reliability. This is especially true of instruments designed to explore the topography of other planets or asteroids where size,weight and prime power are at a premium, and it has already been mentioned that NASA is exploring the feasibility of ranging from Earth to the inner planets using this technology[8].

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Degnan and McGarry, SPIE Vol 3218, Laser Radar Ranging and Atmospheric Lidar Techniques, pp. 63-77, London, UK, Sept. 24-26, 1997

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REFERENCES

1. J.J. Degnan, "SLR2000" in *Satellite Laser Ranging in the 1990's : Report of the 1994 Belmont Workshop*, *NASA Conference Publication 3283*, pp. 101-106, 1994.

2. J.J. Degnan, "SLR2000: An Autonomous and Eyesafe Satellite Laser Ranging Station", *Proc. Ninth International Workshop on Laser Ranging Instrumentation*, pp. 312-323, November, 1994.

3. J. McGarry, J. J. Degnan, P. Titterton, H. Sweeney, B. P. Conklin, and P. J. Dunn, "Automated Tracking for Advanced Satellite Laser Ranging Systems", *Proc. Spring SPIE Meeting, SPIE Vol. 2739*, pp. 89-103, Orlando, FL, April 10-11, 1996.

4. J.J. Degnan, J. McGarry, T. Zagwodzki, P. Titterton, H. Sweeney, H. Donovan, M. Perry, B. Conklin, W. Decker, J. Cheek, A. Mallama, and P. Dunn, "SLR2000: an inexpensive, fully automated, eyesafe satellite laser ranging system", *Proc. Tenth International Workshop on Laser Ranging Instrumentation, Shanghai, PRC, November, 1996*, to be published.

5. J.J. Degnan, "Optimal Design of Q-switched Microlaser Transmitters for SLR", Ibid.

6. P. Titterton and H. E. Sweeney, "Correlation Processing Approach for Eyesafe SLR2000", Ibid.

7. J. McGarry, "SLR2000 Performance Simulations", Ibid.

8. J. J. Degnan, "Compact Laser Transponders for Interplanetary Ranging and Time Transfer", Ibid.

9. K. Hamal and B, Greene,"Second Harmonic Generator T/R Switch" , Ibid.

10. J. J. Zayhowski and C. Dill III, "Diode-pumped passively Q-switched picosecond microchip lasers", Optics Letters, 19, pp. 1427-1429, 1994.

11. J. J. Degnan, "Optimization of passively Q-switched lasers", IEEE J. Quantum Electronics, vol. 31, pp. 1890-1901,1995.

12. M. Selden, C. Steggerda, R. Stringfellow, D. McClure, C. B. Clark, and G. Bianco, "Instrument Development and Calibration for the Matera Laser Ranging System ", Ibid.

13. P. Titterton, H. Sweeney and T. Driscoll , "SLR2000 Acquisition Algorithm Assessments", *Electro-Optics Organization Report 95-010*, August 1997.

14. J. J. Degnan, " Millimeter accuracy satellite laser ranging: A review", *in D.E. Smith and D. L. Turcotte (Eds.), Contributions of Space Geodesy to Geodynamics: Technology, AGU Geodynamics Series*, **25**, pp. 133-162, 1993.